

OPTICAL CURRENT TRANSDUCERS FOR POWER SYSTEMS: A REVIEW

A paper prepared jointly by the **Emerging Technologies Working Group**, Power Systems Instrumentation and Measurements Committee and the **Fiber Optic Sensors Working Group**, Fiber Optics Subcommittee, Power Systems Communications Committee.

Abstract: The technology of the optical measurement of current is reviewed. Several fundamentally different approaches are described. Implementations from a number of manufacturers are examined so as to highlight the similarities and the differences. Experience with optical current transducers is reported. The question of interfacing to an optical current transducer is discussed. The special problems posed by calibration of this kind of instrument are reviewed.

Keywords: optical current transducers, interfacing, calibration, instrumentation standards

INTRODUCTION

Over the last few years, current measurement systems based on optical devices have been developed. A number of quite different optical current transducer (OCT) systems are now on the market or undergoing field trials. They all use optics to isolate a high-voltage part of the system from a grounded part, as illustrated in Figure 1.

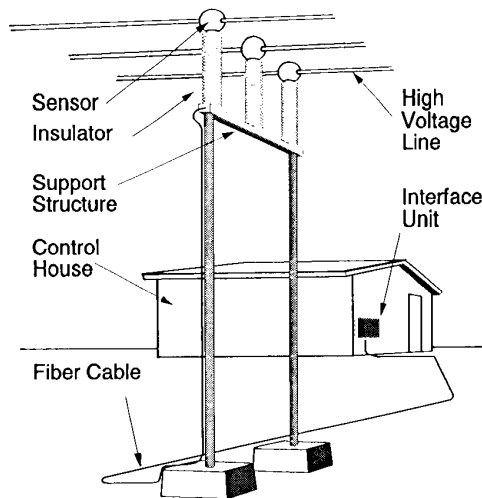


Figure 1. Essential elements of OCT system

It would be misleading to think of an OCT as an optical current *transformer*. OCTs are optical and electronic measurement systems. We shall see below that there are actually many different ways to make an OCT, and most are not based on the transformer principle.

Because an OCT is electronic, a fundamental way an OCT differs from a CT is in the signal power involved. In all the OCTs considered here, the current being measured is represented, as it is transmitted from high potential to ground, as modulated light. In a CT, the secondary signal has a power level of several watts. The power in the optical part of the OCT is typically a few μW .

Optical systems seem first to have been used for high voltage current measurement in the late 1960s and early 1970s, when several different approaches were reported [1-4]. The technology was diverse enough to warrant review by the late 1970s and early 1980s [5-8]. Significant diversity still exists, and another review is justified, this time of the systems commercially available.

Diversity is present in all elements of the system shown in Figure 1. The sensor itself may be optical or electronic, so the high-voltage part of the system may be active or passive. The insulator may be ceramic or polymer—it may be used to support the OCT or it may be suspended from it. Typically, but not universally, it contains an optical fiber carrying the OCT output signal. The way the current information is encoded in the fiber varies from system to system. This affects the design of the receiver at ground potential. An interface unit connects the OCT system to the user device, which may be a relay or a meter or other equipment.

The optical current transducer has several advantages over a conventional device. One is light weight. The optical sensor may be much lighter than a conventional oil filled CT of similar ratings. This lighter weight allows for savings during installation; the support structure is smaller, a smaller crane can be used, and installation time is shorter than for a conventional CT. Other advantages include noise immunity and safety: since the insulating part of an OCT consists only of an optical fiber and a fairly standard insulator, the device is less likely to fail catastrophically than a conventional current transformer.

The purpose of this paper is to review the technology in general, and in particular the different design solutions explored by the OCT manufacturers.

The paper is not intended to be a "Shoppers Guide" for OCTs, and the OCT designs discussed are not identified by

manufacturer. The paper shows that the optical measurement of current in a high-voltage power system has been commercialized in some applications. The devices which have emerged from the laboratory compare with the conventional CTs that have been developed over about the last 80 years in terms of accuracy and stability. Greater use of the technology is likely to result from the continuing contributions of a large number of investigators.

In order to organize the discussion of the different approaches that have been used to implement optical current transducers, we have arranged them in a taxonomy based on increasing order of difference from the conventional current transformer (CT), and we have separated the question of how the optical signal is analyzed. Note that while our designation of sensor types is arbitrary, it serves the useful purpose of providing a classification system. We begin with a summary of the major classes of transducer.

Type 1. Conventional CT with optical readout

The current transformer is such a well-described device that it needs no discussion here. Add to such a CT an insulated optical information channel to replace the copper wire output, as shown in Figure 2, and the advantages of both conventional and optical devices are retained.

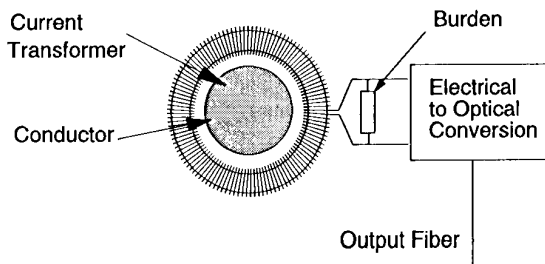


Figure 2. Conventional CT with optical readout

The several methods to convert the current transformer output into optical form will be discussed in a later section.

Type 2. Magnetic concentrator with optical measurement

In this approach, a magnetic circuit surrounds the conductor, but instead of the magnetic loop forming the core of a transformer, the field inside the magnetic core is measured optically in an air gap, as shown in Figure 3.

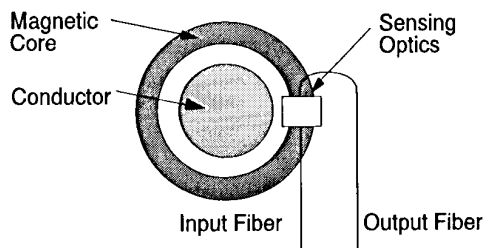


Figure 3. Magnetic concentrator with optical measurement

An advantage of this approach is that the optical path is short and simple, and only a small amount of optical material is needed.

The principles of the optical measurement of magnetic field, applicable to this and the optical methods of Types 3, 4 and 5, will be discussed below.

Types 3 and 4. Optical path surrounding conductor

If the mechanism by which magnetic field is converted into an optical effect can be distributed around the current carrying conductor, a closed optical path surrounding the conductor will measure the current in a way analogous to the magnetic core of a conventional CT. In our taxonomy, this is the first of the optical measurements to contain no ferromagnetic components. There are two variations:

Type 3. Bulk optics

The optical path is inside a block of optically active material, and encloses the conductor exactly once, as shown in Figure 4. This kind of device is analogous to an optical implementation of the conventional CT.

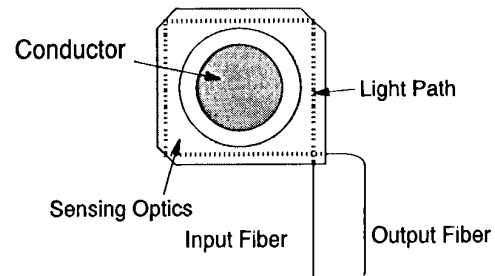


Figure 4. OCT using bulk optics

Type 4. Optical fiber

Here the optical path is inside a fiber that can be wound around the conductor an arbitrary number of times to achieve the desired sensitivity. Figure 5 shows the arrangement.

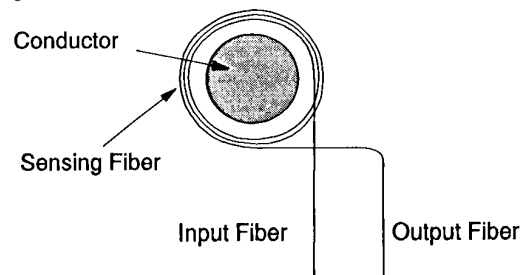


Figure 5. Fiber optics based current measurement

Type 5. Witness sensor

This is the last of our major categories of optical current transducers, and the only one in which the measurement does not completely surround the conductor. Instead, the magnetic field at a point near the conductor is sensed, as in Figure 6. Because the device does not measure around a closed path, it is not really a true *current* transducer.

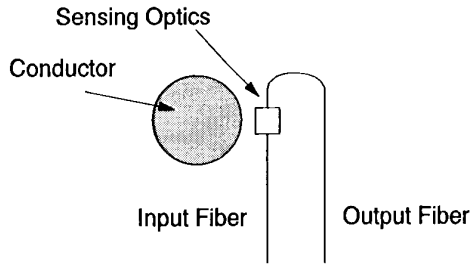


Figure 6. Witness sensor

PRINCIPLES

For almost a century it has been normal practice to provide a measurement signal isolated from high voltage by measuring the magnetic field associated with the current. The current is given by the integral of the field around a closed path enclosing the current carrying conductor. The spatial distribution of the magnetic field depends upon the location of the return path of the current, and can be affected by other nearby circuits. However, provided the integration is carried out over a closed path, the actual shape of the path is immaterial. Ampere's Law may be written:

$$I = \oint \mathbf{H} \cdot d\mathbf{l} \quad (1)$$

where I is the current, \mathbf{H} the magnetic field and $d\mathbf{l}$ the path element. This expression for current can be mechanized in a number of ways. Symmetrical shapes, such as circles and squares, are convenient to analyze and to manufacture.

While it is not the only way to convert a current into an optical effect, the **Faraday effect**^{*}, or **magneto-optic effect**, is used in most optical sensors of types 2, 3, or 4. (In type 1, the problem is one of converting an electrical signal rather than a magnetic field into optical form.) In order to understand the current transducer, we need to examine the optical effects involved.

Light of any arbitrary polarization can be described by considering it to be the sum of two orthogonal components. For linearly polarized components, the two orthogonal directions are simply at right angles. For circularly polarized components, right- and left-rotations are orthogonal. Power engineers might be reminded of positive and negative sequence components. (The analogy can be extended. Both power systems and optical systems can be described by a convenient matrix notation. And just as in modelling a power system, a transform can be written to convert between an a , b , c phase representation and 0, 1, 2 sequence components, in optics it is possible to transform between equivalent linear and circular representations of any polarization state.[9])

In general, the transparent glasses or crystals used to construct Faraday effect devices exhibit the property that the value of the refractive index depends on the direction of

propagation and the polarization of the light. (The directional properties of the electric field vector \mathbf{E} of the light wave define its polarization state.) The refractive index of the crystal has different values for two mutually orthogonal polarizations of the light wave. The property whereby a material possesses two refractive indices is known as **birefringence** [10]. In glasses the birefringence can originate from permanent internal stresses that depend on the thermal history of the material, or from temporary internal stresses created from thermal transients that occur when the ambient temperature changes. In crystals, the crystal structure itself can also produce birefringence.

As far as we know, there are no commercial systems using this approach. It will not be discussed further.

In the next three sections of the paper we will describe the principles of optical current measurements, examine the performance requirements, and report experience with practical transducers.

The maximum and minimum indices are associated with **slow** and **fast axes** of the material, since refractive index is the ratio of the speed of light in a vacuum to its speed in the medium. This difference in propagation velocity in the material introduces a *phase shift* between the two polarized components of light. The term birefringence is commonly used in the restricted sense of applying to a material that affects *linearly* polarized components of light in this way. Linearly polarized incident light in general then emerges elliptically polarized. (It is also possible that the parameters are such that the emerging light is in one of the two special cases of elliptical polarization, circular or linear.)

In contrast, if the same light (modelled as two orthogonal linearly polarized components) passes through a material that preserves the phase but couples energy between the two linearly polarized components, it will still be linearly polarized when it emerges. The plane of polarization will have rotated. This property is known as **optical activity**. The effect is distinct from the classical birefringence, although the material could in fact be analyzed as possessing different refractive indices for counter-rotating circularly polarized modes. Another name for optical activity is therefore **circular birefringence**. An optically active material is ideally isotropic (such as a glass or a liquid) and (again ideally) exhibits no (linear) birefringence.

The Faraday effect is a modulated optical activity: a rotation of the plane of polarization of linearly polarized light in proportion to a magnetic field through the material. The strength of this effect is expressed by the **Verdet constant**. An optical current transducer functions by passing

^{*}Optical terms that might not be familiar will be set **bold face** when they are first introduced.

linearly polarized light through a material that exhibits the Faraday effect: the plane of polarization is rotated in proportion to the field and the path length. Strictly,

$$\theta = \mu V \int \mathbf{H} \cdot d\mathbf{l} \quad (2)$$

where θ is the rotation of the polarization azimuth, μ is the relative permeability, V is the Verdet constant, and \mathbf{H} and $d\mathbf{l}$ are the components in the direction of propagation. The similarity with (1) is clear. In practice, the Verdet constant varies with wavelength, and is temperature dependent. These effects must be dealt with in a practical OCT.

For the material to be useful as a current transducer, the light must first be linearly polarized. Suitable light can easily be produced by passing unpolarized light through an optical element called a **polarizer**, which can be regarded as selecting only light of a particular polarization from the incident energy. The rotation of the plane of polarization must then be measured. The rotation is not a directly detectable parameter. Photodetectors are not sensitive to the polarization of light, only to the optical power, which is proportional to the square of the \mathbf{E} field. In other words, even if the plane of polarization of the incident light is rotated in the material, more than just a photodetector is needed to detect this. Three different solutions are described below.

While there are other transduction mechanisms for fiber-based OCTs [11], such mechanisms do not appear to have been developed as extensively as the Faraday devices, and will not be examined further in this paper.

ANALYSIS METHODS

We have organized and labeled the various approaches used to analyze the optical signal produced by a Faraday sensor arbitrarily. We start by examining one of the simpler analysis methods, and use the discussion to introduce some of the general problems of optical measurements.

Method A. AC/DC method

The measurement is made by examining the linearly polarized light emerging from the sensor by means of a second polarizer (termed an **analyzer**). The magnitude of the linearly polarized component in any arbitrary direction can be extracted by properly orienting the analyzer. From this point on, only the *power level* of the light is important.

If there is an angle α between the transmission axes of the polarizer and the analyzer, the light power P_{det} at the detector is given in terms of the input power P_{in} by

$$P_{\text{det}} = P_{\text{in}}(\cos\alpha)^2 = \frac{1}{2}P_{\text{in}}(1 + \cos(2\alpha)) \quad (3)$$

assuming there is no insertion loss. A representative optical arrangement is shown in Figure 7, which also shows the polarization state of the light at various parts of the system.

Note that the polarization at the detector is not fixed because the output fiber does not preserve the polarization state. If the fiber is long enough, some tens of meters, **mode mixing** will depolarize the light.

Figure 7 is drawn for a Type 2 transducer, using bulk optics, but the ideas can be adapted for other types. In Type 3 sensors, the optical path includes reflections inside the Faraday material. In Type 4 sensors, the Faraday material is a fiber. If the polarizer and analyzer are not mounted as shown near the Faraday element, polarization-maintaining fiber is needed between these components [12,13]. The polarizer and analyzer can be implemented using fibers, too.

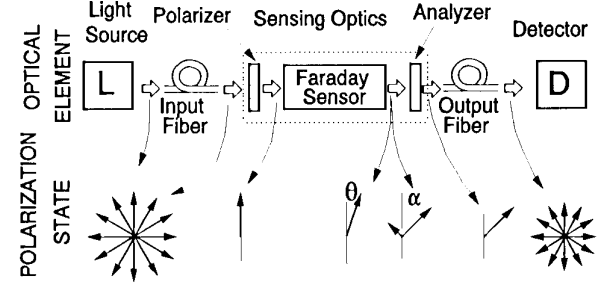


Figure 7. Typical arrangement of optical components and polarization components in Faraday sensor

Typically, the polarizer and analyzer are arranged at an angle α of $\pi/4$. With no applied field, the optical power input to the detector is then only half the input power. If the rotation angle θ is small, the *change* in detector output is practically a linear function of the field. From equation (3), where α is replaced by $(\pi/4 + \theta(t))$, the optical power at the detector is given by

$$P_{\text{det}}(t) = \frac{1}{2}P_{\text{in}}(1 - \sin(2\theta(t))) \quad (4)$$

assuming there is no birefringence. The detector signal will thus consist of a steady dc level, and a superposed ac component that represents the modulation due to the Faraday effect. The ac component is given by

$$P_{\text{ac}} = \frac{1}{2}P_{\text{in}}\sin(2\theta(t)) \quad (5)$$

$$= P_{\text{in}}\theta(t) + \text{higher order terms}$$

and the dc component is simply

$$P_{\text{dc}} = \frac{1}{2}P_{\text{in}} \quad (6)$$

While the ac part of the signal contains information about the current, it cannot be used alone to represent the measurement. This is because a change in the optical attenuation or light source power would appear to have the same effect as a change in the modulation. The output can be normalized by computing the ratio of the ac to the dc components

$$\frac{P_{\text{ac}}}{P_{\text{dc}}} = 2\theta(t) = AI(t) \quad (7)$$

where $I(t)$ represents the current being measured, and A is a constant depending on the design. The value thus obtained is independent of the value of the optical power, P_{in} .

Method B. Sum and difference method

It is also possible to use the outputs of two analyzers, arranged at $\pm\pi/4$, or equivalently, a **polarization beam-splitter** such as a **Wollaston prism**, and compute the ratio of the difference between the two polarization components to their sum. The output of the two analyzers, P_{A1} and P_{A2} is given by

$$P_{A1}(t) = \frac{1}{2}P_{in}(1 + \sin(2\theta(t))) \quad (8)$$

and

$$P_{A2}(t) = \frac{1}{2}P_{in}(1 - \sin(2\theta(t))) \quad (9)$$

As far as sensitivity and the effect of birefringence are concerned, the result is identical with the calculation for the ac/dc method. The optical hardware is a little more complex, but the method gives improved rejection of optical common-mode noise.

Method C. Complex analysis method

While Faraday materials are ideally not (linearly) birefringent, practical devices that use the Faraday effect suffer a distortion of the output that can be attributed to temperature- or stress-induced linear birefringence. The light incident upon the analyzer is therefore elliptically polarized. Although one author has described a technique whereby careful alignment of the incident light and the optical axis of the sensor crystal [14] is used to largely cancel the temperature-dependent birefringence, this approach does not seem to have been employed in a commercial product.

A full analysis of the emerging light, including its elliptical polarization, requires subjecting the Faraday material to a number of polarization angles and monitoring the output. This method has been used by a number of investigators [15,16] and is described tutorially in [17] with respect to a voltage sensor. It is beyond the scope of this paper to describe this approach in detail. The interested reader is urged to study the references cited above.

PERFORMANCE REQUIREMENTS

The requirements that have been applied to current *transformers* depend on the application. They are spelled out in national and international standards, such as IEC 185: 1987, "Current Transformers" [18] and ANSI/IEEE C57.13-1978 "Requirements for Instrument Transformers" [19]. These documents address the parameters that are important in ensuring that a CT is suitable for its application. Thus, general requirements such as insulation levels and temperature rise are covered, as well as the requirements in the area of rating and accuracy.

In general, the performance of a measurement system can be described in terms of a handful of interrelated parameters. In the following discussion we will use analog parameters. Similar arguments can be made for digital measurements.

Frequency response is a parameter that will be familiar to many readers, probably as a specification of amplifier performance. The term dynamic range is also used in this application. The dynamic range of a system is the ratio of the largest signal that can be handled satisfactorily to the smallest. Large signals will saturate the system, small signals will disappear into the noise. Dynamic range is therefore associated with parameters such as signal-to-noise ratio, smallest discernable signal, and harmonic distortion.

Many forms of noise have an extended spectral distribution, so that typically an increase in the frequency response will introduce more noise into a measurement, and the dynamic range will suffer. Conversely, a noisy measurement can often be cleaned up by filtering the signal.

Even if the measurand is within the passband and dynamic range of the measurement system, the reading at any value could still be in error. The system nonlinearity describes how this error varies as a function of the signal

amplitude. Variations of the error with time and temperature define the stability of the system.

Unfortunately for our needs, the CT standards do not address measurement requirements in a way that is directly useable for OCTs. Frequency response is not specified—in fact it is not even mentioned in the standards. Signal-to-noise ratio is not mentioned either, nor is harmonic distortion. Stability is not specified. Dynamic range is described in terms of the ratio error as a function of the current.

The parameters that are standardized, ratio error and phase error, can usually be adjusted to arbitrarily small values at any given operating point (such as rated current) in an electronic device such as an OCT. Therefore, while we assume that an OCT should be no less qualified than a CT, existing standards for CTs will be of limited use. It is clear that two OCTs could still be very different even if they are within the error limits set by standard for CTs. This could be critical in some applications: a translation of CT standards to OCTs would not ensure their compatibility in a differential protection scheme. Further, it has been suggested [20] that the difference observed between the output wave-shape of a conventional CT and an OCT is due to (unspecified) filtering by the CT.

Work is presently underway in IEEE to produce new standards. The two working groups that produced this paper are working on a Trial Use Standard for current measuring systems that use optics. This work has been designated Project 1304 (P 1304) by the IEEE Standards Board. It would be unreasonable to standardize the way current is measured, that is to specify one of the sensor Types 1 to 5, or analysis Methods A to C. The standard will instead address the performance of the system, and describe ways to measure that performance (see Calibration, below). Another

Project (P 1331), assigned to the Power System Relaying Committee, addresses the requirements on an analog system furnishing a signal to protective devices. Presumably, the work of P 1304 will enable the user to be certain that a given device will meet the requirements laid out in P 1331.

Interfacing

The nominal output of a current transformer is usually 5 A; 1 A is also used. A large value of secondary current was chosen, almost a century ago, to give noise immunity (currents of similar magnitude are unlikely as interference signals), and to provide sufficient energy to operate electro-mechanical relays or meters. For OCTs, alternative low energy outputs (typically a few volts or a few mA) have been preferred [21]. The design of the power supply (and the impact on the station battery) become problematical if a large current has to be supplied without distortion. In any case, adequate isolation from interference is provided by the optics, and modern metering and relaying devices do not require much energy to operate.

Given that a low energy output will be used, the question of just what form that should take has yet to be answered. The designers of a digital Type 1 system have solved the problem by designing the equipment at the other side of the interface. One manufacturer of a Type 3 system has reached agreement with a meter company on a 10-mA signal. This amounts to a choice of scale factor (mA out for Amps in). Bearing in mind all the other important parameters that must be specified to define system performance, scale factor seems like a rather minor decision. In fact, for the analog systems, it makes little difference whether the output is a small current or a small voltage. The choice has not been standardized, and is at present decided by the user.

Calibration

The most stringent of the current transformer standards for metering CTs specifies a class of accuracy of 0.1% maxi-

mum ratio error [18]. Assume a similar requirement for OCTs. As a rule of thumb, it is preferable that the system that calibrates the transducer must be an order of magnitude better. Its uncertainties must be in the order of 0.01% or 100 ppm. Such calibration equipment may be used by the manufacturer or the user. The uncertainties must be ten times lower than this, ie 10 ppm, in the equipment at the national standards laboratories that is used to verify the accuracy of the manufacturers' equipment.

In principle, any existing CT calibration method could be used with OCTs if there were means of amplifying the signal output to the level of conventional CTs. The amplifier would have to be well characterized, and in practice it would be very difficult to achieve a low enough uncertainty.

Several calibration methods for low energy systems are reviewed by Kirkham [22]. The question of equipment for the most accurate calibrations has been addressed by So [23, 24]. These authors conclude that calibration is possible with uncertainties no greater than for conventional CTs.

While it will be necessary to ensure that the measurement error is sufficiently small at rated current and frequency, methods will also have to be specified to verify the frequency response, the dynamic range and the stability of the OCT. With some exceptions (see [25] and [26] and their references), these factors have scarcely been considered in calibrating instrument transformers.

One aspect of the optical current transducer that makes it different from the CT is the fact that the system comes in several parts. Whereas a failure of a CT requires replacement of the complete device, OCTs could fail in ways that are most economically repaired by replacing only part of the system. This means that it may be necessary to recalibrate the OCT after part of it has been replaced. This, in turn, may necessitate removing the OCT from the power line. Because of this, it may be advantageous to perform such recalibration in the field, a possibility that has not required much consideration until now.

PRACTICAL TRANSDUCERS

Any of the sensor methods could, in principle, be used with any of the analysis methods. The combinations that have been used in commercial systems are shown in Table 1. For simplicity, we will discuss the practical systems only in terms of the kind of sensor used, and not with respect to the analysis method employed.

Type 1. Conventional CT with optical output

The current transformer that is used in this approach can differ from the design of a normal high voltage CT. Since the CT needs no high voltage insulation, a shorter iron length is possible. The burden is also constant, and consumes very little power. This allows a further reduction in core dimensions, and also a greater freedom to use air-gap cores, ferrite, or an air-cored transformer, to obtain good high frequency performance.

Table 1. Combinations of sensor types and analysis methods used in practice

Sensor Type	Analysis Method		
	A AC/DC	B -/+	C Complex
1. CT	*		
2. Concentrator	*	*	*
3. Bulk Optics	*		*
4. Fiber Optics	*	*	*

Three commercial OCTs of this general design have been made. One uses electronics to produce a digital optical output, one uses a Faraday sensor and one uses a piezo-

CONCLUSIONS

Optical CTs are small, integrated, passive devices to mount on the conductor, while the measuring electronics are housed at ground potential in a shelter or building. Although qualitatively very simple, most of these sensors require care in design and construction because the optical response is small. Full-scale polarization rotation is likely to be only a few degrees, corresponding to a few percent modulation of light intensity. Designs to optimize stability are required, as is compensation for environmental effects on all components, including any temperature dependence of the magneto-optic effect itself.

Demonstration systems have shown the successful use of optical sensors in both revenue metering and protective relay systems. They have also shown that stable and accurate performance in the substation environment is obtainable with proper design. The capabilities and features of optical current sensing will open the possibility of a high reliability, wide dynamic range sensor that will provide an optimum interface between high voltage systems and electronic equipment expected to monitor and control those systems.

ACKNOWLEDGEMENTS

This paper is a compilation of the work of many members of the Working Groups shown as authors. Harold Kirkham of JPL, Chairman of the Working Groups, provided the tutorial material and did much of the assembly, editing and document production. Scott Weikel of ABB, in addition to furnishing information about the devices made by his company, provided editorial and logistical support. Original material was provided by and critical reviews were performed by Morgan Adolfsson (ABB), Hiroyuki Katsukawa (NGK), Eddy So (NRC Canada), Ed Ulmer (Square D), Bob Wandmacher (3M), and Clarence Zarobila (OpTech). Reviews were also done by Alan Johnston of the High Speed Optical Systems group at JPL, and by Ole Tønnesen's group at DTH Denmark.

This document was prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy, Office of Energy Management Systems, Utility Systems Division, through an agreement with the National Aeronautics and Space Administration.

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difference amplifier, some rejection of common-mode source and optical lead noise can be achieved, along with a doubling of the signal amplitude.

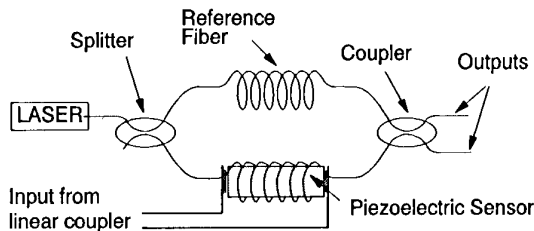


Figure 8. Mach-Zehnder interferometer using fiber optics

Performance

The dynamic range of the Type 1 OCT is defined by the electronics. The largest signal is limited by the demodulation scheme used, and the noise floor is set by optical source intensity and phase noise. In the prototype device, the dynamic range of the OCT is from 1 A to 33 kA, or about 90 dB. The accuracy is within the 0.3% specified by ANSI C57.13 between about 100 A and 30 kA. This 50 dB span would permit simultaneous application to the measurement of nominal and fault currents.

Experience

As of this writing, only laboratory demonstrations have been performed; however commercial testing is planned.

Type 2. Magnetic concentrator with optical measurement

One of the advantages claimed for this approach is that it can readily be retrofitted to existing equipment, since the core is already split [30, 31]. It is also clear that the large air gap should help with system linearity. The small size of the system is also said to be an advantage in retrofitting applications [30, 32].

A possible disadvantage is sensitivity to current in nearby conductors, since the magnetic concentrator is not continuous. Another problem is the nonuniformity of the field in the air gap, and the resultant dependence of the device sensitivity to the position of the optical sensing element. Some papers describing OCTs of this type address the question of the field distribution in the gap [30, 33]. It is pointed out that the concentrator design is a compromise between the desire for a large cross section, with a relatively uniform field distribution, and the general desire for a small cross section, to reduce the size and weight of the overall system. Reference [32] discusses the effect on the error of moving the conductor inside the concentrator, assuming that the Faraday sensor remains fixed in the gap.

The design of the optics must take into consideration the effect of vibration and temperature changes on optical alignment. This is true for any of the optical systems, but especially for Types 2 through 4. For example, stable mountings are required for holding and aligning lenses that focus source light into single mode fiber, or that image an

input source onto an output aperture. Various techniques are used to minimize or eliminate system noise, such as feedback to the laser or LED source for temperature compensation, etc., in addition to the reduction of common-mode effects by taking the ratio of two optical signals.

Performance

In the application for which the current transducers of references [15] and [30-35] were designed, accuracy was not of paramount importance. References [30], and [32-34] describe fault location systems designed to be retrofitted to existing substations, so that size and convenience were important. One of the devices [33] claims room-temperature accuracy better than 1% over a range of current from 250 A to 4 kA, with a residual temperature sensitivity in the order of 0.02%/°C over the range -20 to +80°C. Another device [30] demonstrated a room temperature accuracy of 0.3%, and the ratio error remained below ± 0.5 over the range 0-50°C. These results were essentially unaltered when 3-phase tests were done. Although this work has not been described in detail, it is evident that the error caused by current in the adjacent conductors was negligible.

Experience

As in the case of the Type 1 system, the units are associated with a specific application. A prototype fault location system based on the device described in [30] was installed in a substation from July 1989 until February 1991. The purpose was to test the system performance in the real world, with the usual electrical noise environment and the ambient temperature changes. After the 20-month test, the unit was returned to the factory, where its performance was found to be still within design parameters. In another application, several fault location systems based on the use of optical current transducers were installed in one utility beginning in 1990 [33]. As of April 1993, 600 units have been installed in about 100 substations.

Type 3. Bulk optics

At least four commercial systems of this type have been made in which the light encircles the current conductor once. The light is guided around this path by a high precision piece of optical glass, which is the Faraday material. Before the light enters the body of the Faraday sensor, it is collimated and polarized. The polarizer and analyzer are located at the ends of the fiber, adjacent to the Faraday sensor body, (not shown in Figure 4). A second lensing system is employed to couple the light into a second optical fiber that is used to guide the light to the photodetector, where the amplitude information is recovered. In two implementations for gas-insulated substations (GIS), a free-space section is inserted in the optical path, and additional lenses are used to provide fiber-to-fiber coupling [15, 35].

Performance

Material selection for the sensing element is a trade-off among many factors, including optical characteristics,

operating range, and temperature stability. The desire for stability and wide dynamic range leads to the selection of a material with small Verdet constant.

Some materials with small Verdet constants also possess Verdet constants that have small temperature coefficients. In fact, for one manufacturer's material selection, the temperature dependence of the OCT over a range of -40 to 80°C is such that no temperature compensation is needed for applications in protective relaying [37].

Maintaining *on an instantaneous basis* the level of accuracy that is required to comply with (for example) the metering specifications of IEC 185 is difficult because of the noise generated by the photodetector. However, the integrating characteristic of the watt-hour meter reduces the effect of this noise source dramatically. This filtering may allow a system with wide dynamic range to serve both metering and relaying applications, where several CTs are presently used. [36]

Experience

The first field installation for a bulk optic current sensor was in 1986, as a metering class transducer [37]. For a comparison test, the OCT was placed in series with a conventional free-standing oil-filled revenue metering accuracy CT on one phase of a 161 kV transmission line. Both sensors fed solid state revenue meters. This approach was taken because the objective of the field test was to monitor the stability of the sensor when operating in a substation environment. One conventional potential transformer was connected to both meters. At the end of the two year trial, the OCT had operated continuously for one year. Over this period the accumulated deviation between the OCT system and the conventional system was 0.08%.

At about the same time, a GIS system using a free-space optical link was undergoing tests in a 77 kV station [35]. Satisfactory operation of the system for a period of 20 months (ending in February 1989) was reported. Ratio errors during the test were below 1%, except where the current was small (<1% of rated current) and quantization error in the 12-bit A/D convertor became significant.

Since that time other optical metering systems have been installed at several utilities. Installations from 23 kV to 345 kV have been completed to date [20, 36]. In addition, 500 kV installations are planned for 1993.

A protection system using bulk optic sensors interfaced to a digital line protection relay was installed in 1990 [38]. The relay system was designed to protect a three-phase, air insulated, 161 kV transmission line that runs from a generating station to a major substation. The protection scheme used by the relay system was a directional-comparison carrier-pilot blocking scheme utilizing distance elements for phase-to-phase protection and directional overcurrent elements for ground fault protection. The equipment at each end of the transmission line was comprised of two sets of three OCTs used as the current inputs to the digital relay. Existing

voltage transformers provided the voltage signals to complete the distance relaying inputs. For those faults which have occurred during the year since the installation of the system, all systems have responded as expected.

Type 4. Fiber optics

In an fiber OCT the Faraday rotation occurs within a coil of fiber surrounding the conductor. Sensing fibers are typically single mode fibers, since multimode fibers tend to depolarize light. Such an arrangement does not require the precision machining or aligning of the optical sensing element which is required in some of the classical optics systems described above. Also, using fiber for the sensing element permits the flexibility of adjusting the sensitivity of the sensing coil by adding dopants to the fiber core to change its Verdet constant, or by varying the number of turns around the conductor. The fiber coils can be made quite small and sensitive [39, 40]. However, bending the sensing fiber into a coil induces linear birefringence, which can reduce the response sensitivity of the sensor and increase the variation of the output with temperature. There are two approaches to overcoming the bend birefringence: using a sensing fiber which has high circular birefringence, or using a coil of standard fiber which has been annealed after coiling [39-41].

At least three systems have been produced using this kind of sensor. They differ principally in the analysis method used (see Table 1).

The effects of temperature variations must be eliminated or compensated for in the design. A major source of temperature effects in some experimental systems is the change in the linear or circular birefringence in the sensing fiber with temperature. One approach to minimize temperature effects is to use a reflection mode configuration, in which the light travels through the sensing fiber and then reflects back through the same fiber in the opposite direction [40]. In the reflection mode, the effects of birefringence changes tend to cancel out, while the Faraday rotation is doubled.

Accuracy at lower current levels is limited by the optical power and the signal to noise ratio of the processing circuitry. Filtering techniques are commonly used to remove some of the noise. Unless care is taken, filtering can significantly reduce the frequency response and the phase accuracy. For utility applications, metering level accuracy over a range greater than 1% to 200% of rated current is achievable by adjusting the fiber coil sensitivity and the number of fiber turns so that the coil operates in the linear portion of its response curve over the desired current range.

Experience

Commercial development of current transducers for power utility applications based on fiber optic sensing elements has occurred in France and England as well as in Japan and the U.S. [12, 13, 16, 41]. Field testing of some of the fiber based systems began as early as 1987, but published reports on the performance of these devices are limited at this time.

CONCLUSIONS

Optical CTs are small, integrated, passive devices to mount on the conductor, while the measuring electronics are housed at ground potential in a shelter or building. Although qualitatively very simple, most of these sensors require care in design and construction because the optical response is small. Full-scale polarization rotation is likely to be only a few degrees, corresponding to a few percent modulation of light intensity. Designs to optimize stability are required, as is compensation for environmental effects on all components, including any temperature dependence of the magneto-optic effect itself.

Demonstration systems have shown the successful use of optical sensors in both revenue metering and protective relay systems. They have also shown that stable and accurate performance in the substation environment is obtainable with proper design. The capabilities and features of optical current sensing will open the possibility of a high reliability, wide dynamic range sensor that will provide an optimum interface between high voltage systems and electronic equipment expected to monitor and control those systems.

ACKNOWLEDGEMENTS

This paper is a compilation of the work of many members of the Working Groups shown as authors. Harold Kirkham of JPL, Chairman of the Working Groups, provided the tutorial material and did much of the assembly, editing and document production. Scott Weikel of ABB, in addition to furnishing information about the devices made by his company, provided editorial and logistical support. Original material was provided by and critical reviews were performed by Morgan Adolfsson (ABB), Hiroyuki Katsukawa (NGK), Eddy So (NRC Canada), Ed Ulmer (Square D), Bob Wandmacher (3M), and Clarence Zarobila (OpTech). Reviews were also done by Alan Johnston of the High Speed Optical Systems group at JPL, and by Ole Tønnesen's group at DTH Denmark.

This document was prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy, Office of Energy Management Systems, Utility Systems Division, through an agreement with the National Aeronautics and Space Administration.

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